Timing Reference Sources

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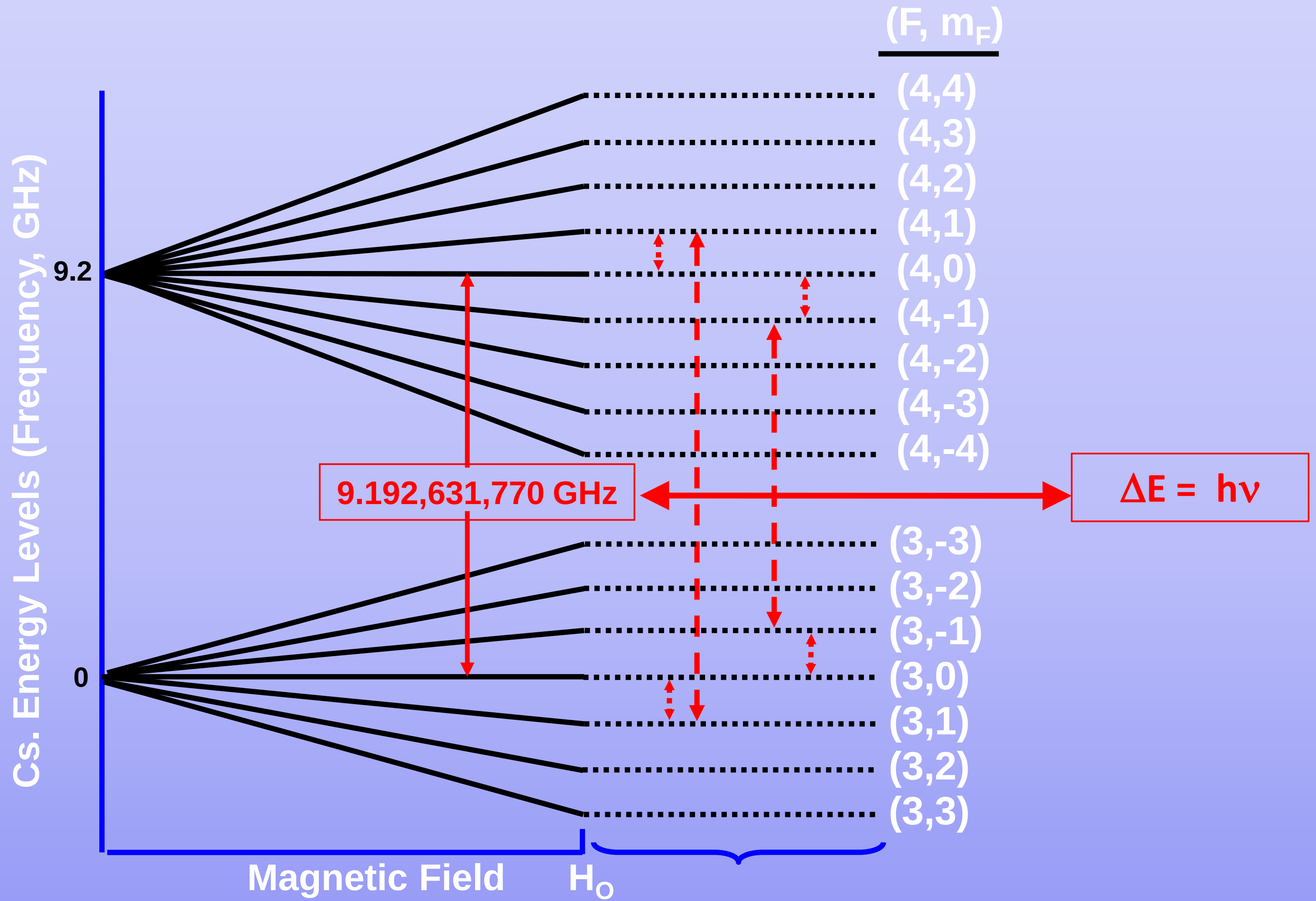
Primary Sources
for Time and Frequency

- **Atomic Clocks**
- **Time and Frequency Transfer**
- **GNSS**
- **Conclusions**
- **Extra Slides**

Atomic Frequency Standards:
Produce Frequency Locked to an Atomic Transition

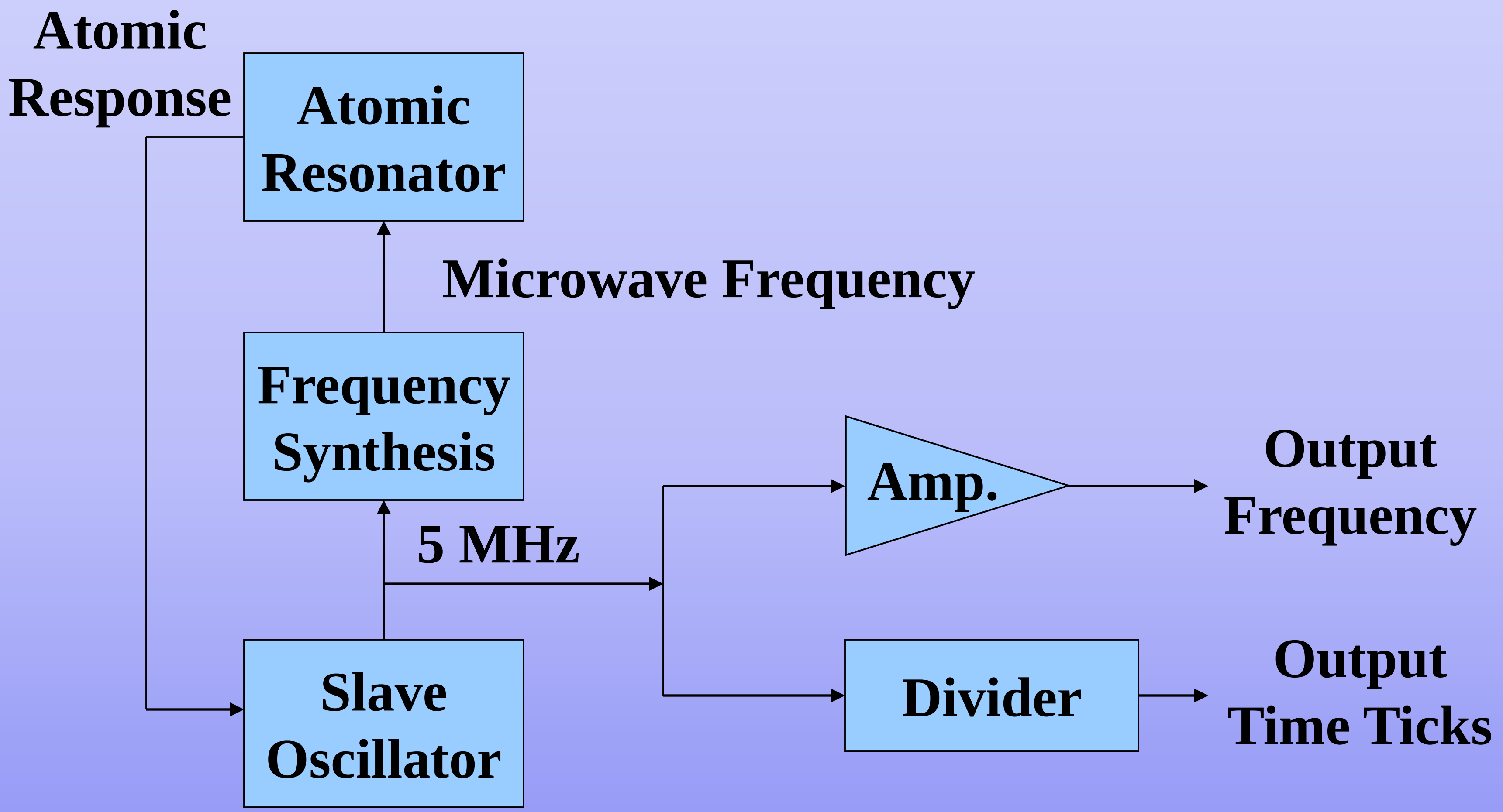


Basic Passive Atomic Clock

1. Obtain atoms to measure
2. Depopulate one hyperfine level
3. Radiate the state-selected sample with frequency ν
4. Measure how many atoms change state
5. Correct ν to maximize measured atoms in changed state

Block Diagram of Atomic Clock

Passive Standard



Types of Commercial Atomic Clocks

- Cesium thermal beam standard
  - Best long-term frequency stability
- Rubidium cell standard
  - Small size, low cost
- Hydrogen maser
  - Best stability at 1 to 10 days (short-term stability)
  - Expensive several $100K
- Chip Scale Atomic Clock (CSAC)
  - Very small size, low power
- Note that new clocks are under development!

Holding a Microsecond after Loss of Sync (circa 2015)

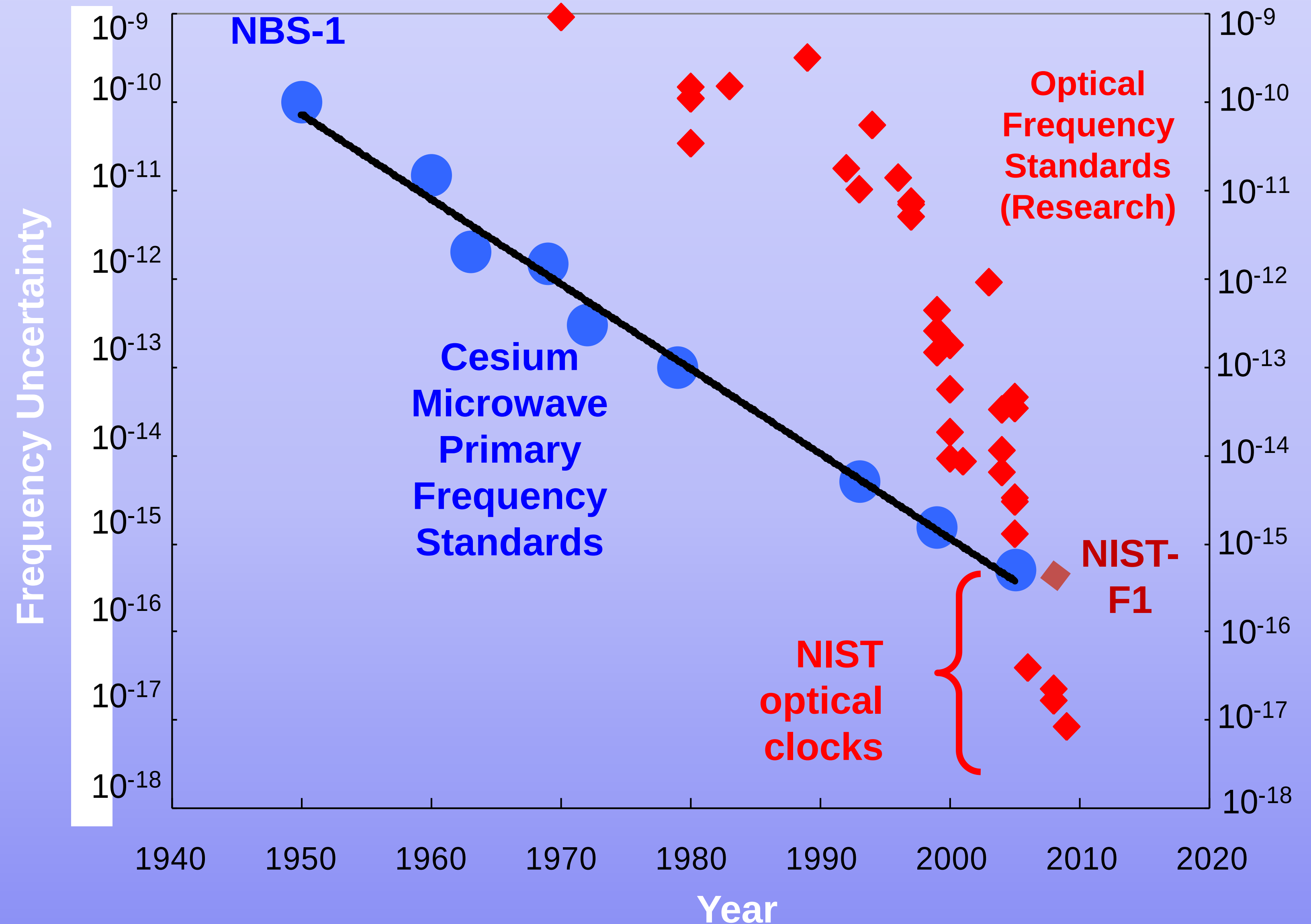
	Temperature Controlled Crystal Oscillator (TCXO)	**Oven Controlled Crystal Oscillator (OCXO)**	**Rb Oscillator** (5E-12/mo. aging)
Range of times to hold a microsecond	10 minutes – 1 hour	1 – 8 hours	8 hours – 3 days
Cost Range	$5-25	$50-150	$500-1500

Conclusions: Atomic Standards

- Rubidium, cesium, and hydrogen atomic frequency standards share a common theme: the stabilization of an electronic (quartz) oscillator with respect to an atomic resonance.

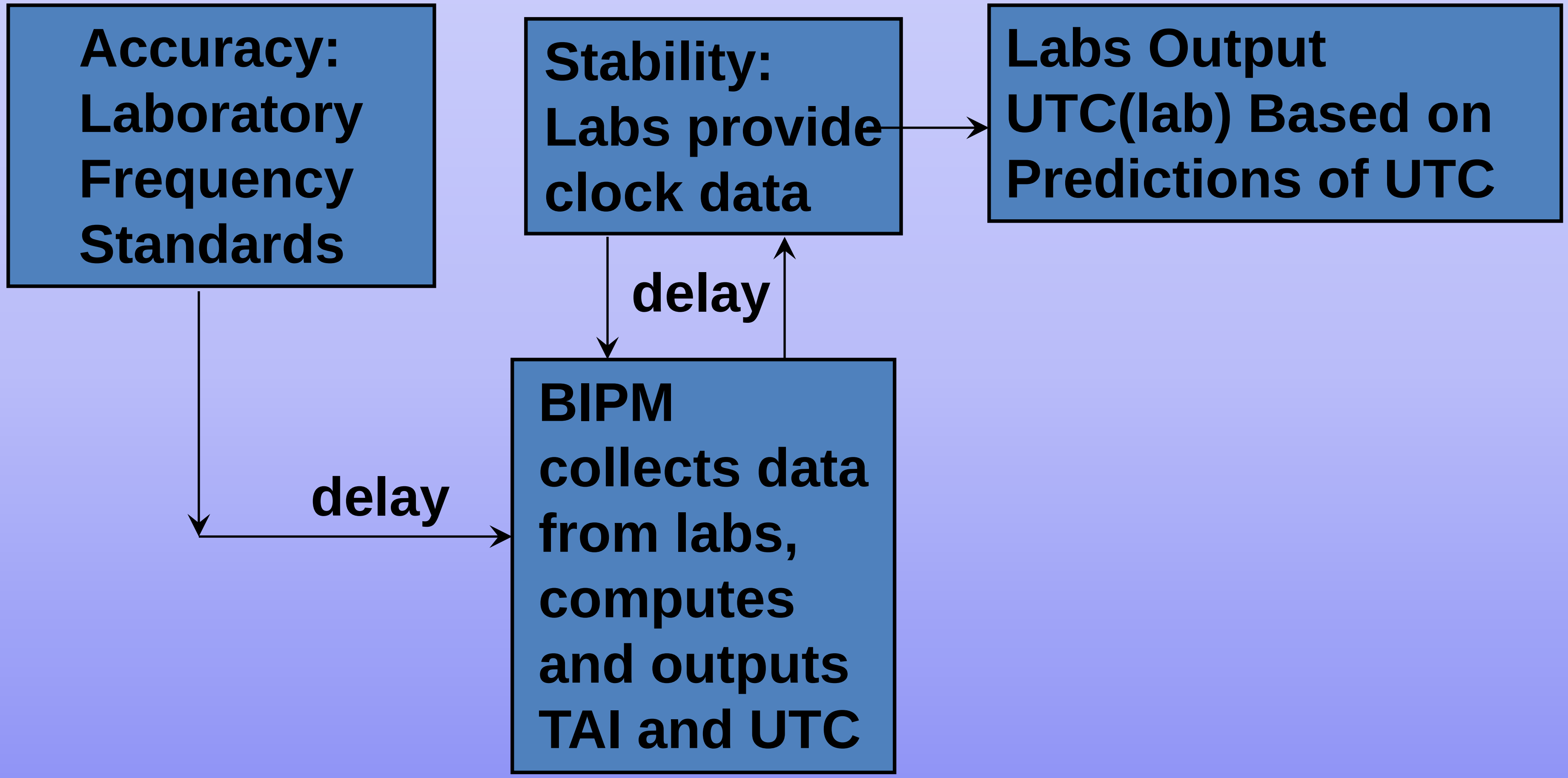
- Although the use of atoms brings with it new quantum mechanical problems, the resulting long-term stability is unmatched by traditional classical oscillators.

Frequency Accuracy:
History of NIST Primary Frequency Standards



The Generation of UTC: Time Accuracy

Any Real Time UTC is only a Prediction,
A PLL with a one-month delay



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Time and Frequency Transfer: How to Deliver a Timing Reference

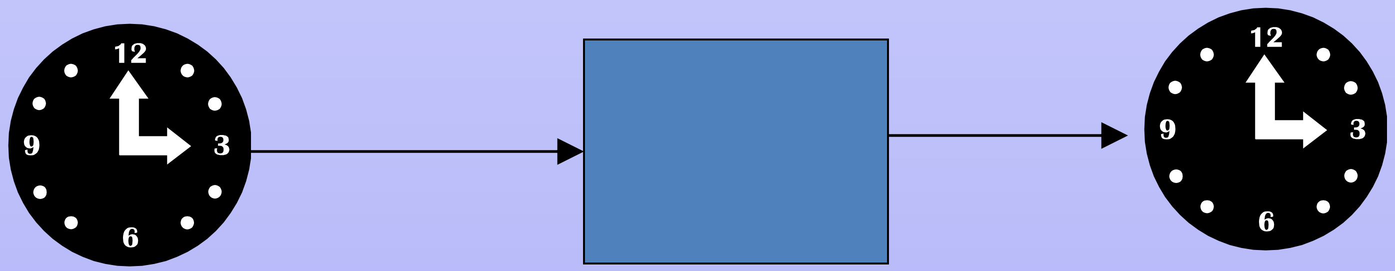
- Time Transfer Accuracy Requires Calibrating Delays

- Imagine writing a letter: “It is now 2 PM– set your watch”
- Seal it in an envelope and drop it in a mail box
- Only useful if you know how long it took to get to you
- Now suppose you timestamped when you sealed the letter and the receiving person timestamped when he got it…

- Time Stability = Frequency Accuracy

One-Way Dissemination or Comparison System

Clock 1 **Clock 2**



Clock 1 Systematics and Noise

Delay, Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Two -Way Comparison System

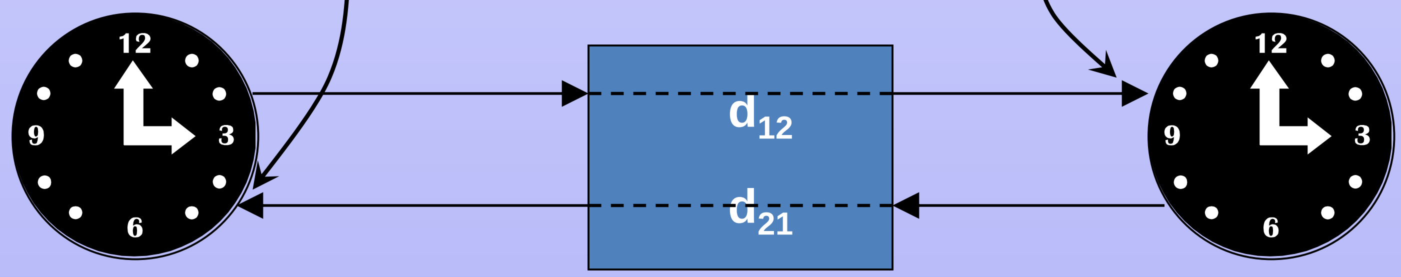
(e.g. IEEE1588 – PTP)

Measure t_{12}= Clock1-Clock2 +d_{21}

Measure t_{21}= Clock2-Clock1 +d_{12}

Clock 1

Clock 2



Clock 1 Systematics and Noise

Measurement Noise and Path Perturbations

Largely Reciprocal:

$d_{21} = d_{12}$

Clock 2 Systematics and Noise

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The Family of Global Navigation Systems

GPS
US
(24+, Now 30
12 IIR
6 IIR-M
12 IIF)

Galileo
EU
(27, Now 11-15
IOC)

GLONASS
Russia
(24, Now 24-27)

Beidou/Compass
China
(35, Now 21)

Two Messages About GNSS

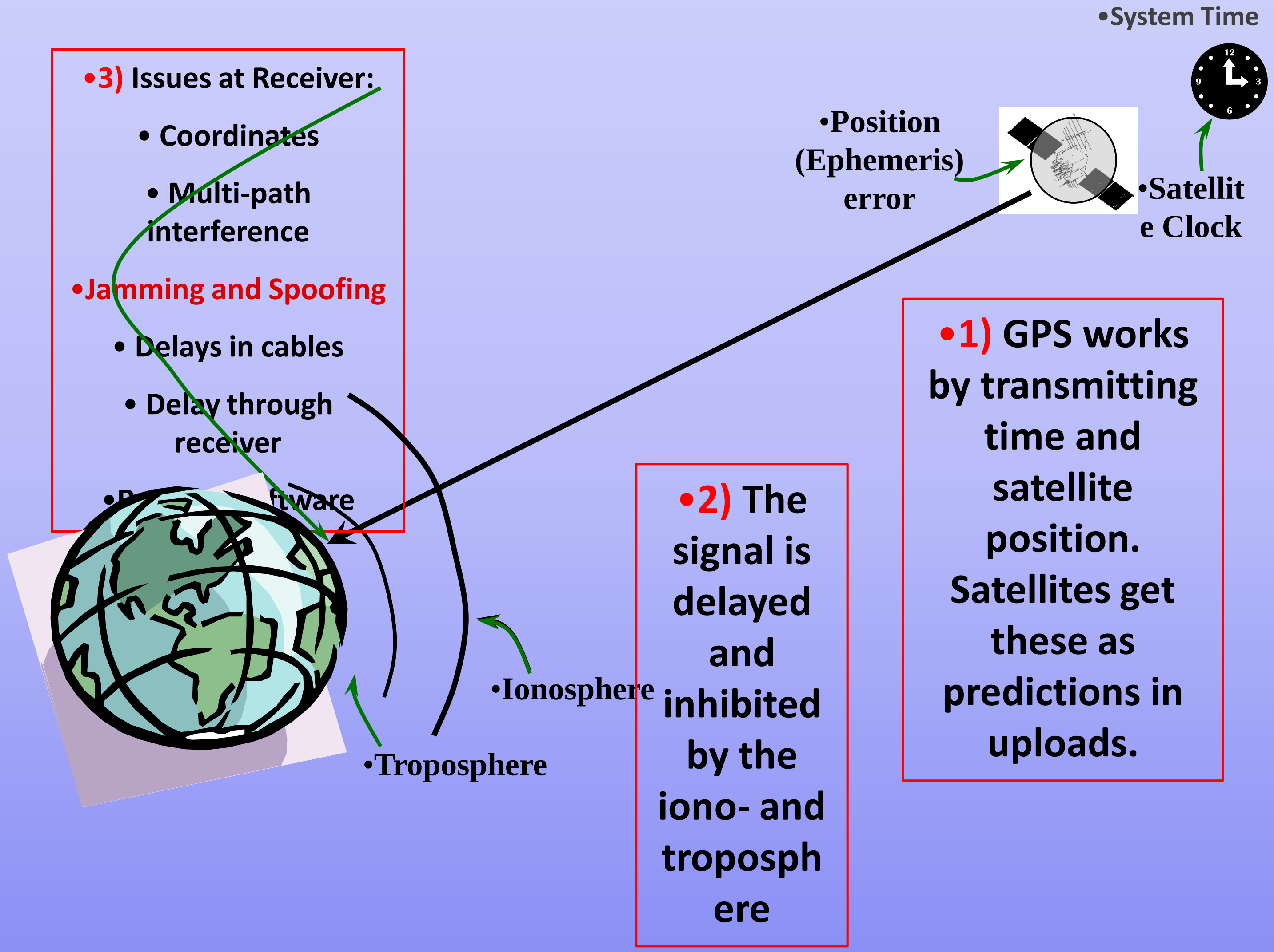
1. GNSS are extremely useful
    1. Constellations are growing
    2. Provide reliable, extremely accurate real-time UTC time and frequency for mostly free
    3. Excellent navigation
    4. A global > $100B industry

2. GNSS signals are dangerously vulnerable to both accidental and intentional interference

GNSS Systems: General Properties

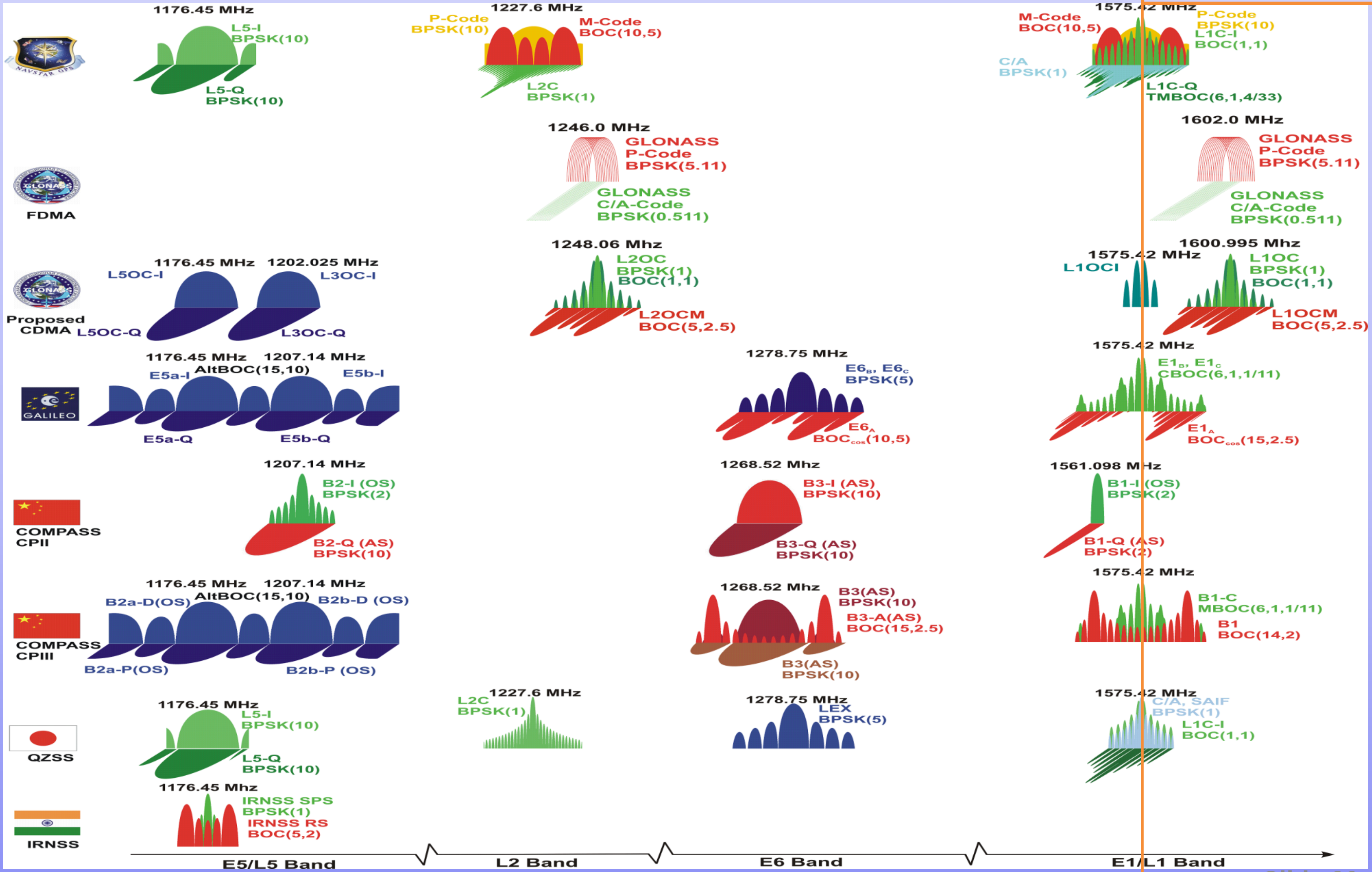
- Position, Navigation, Timing (PNT)
- Four + synchronized timing signals from known locations in space required for navigation
- Two + frequencies measure ionosphere
- Control, Space, User Segments
- Open and Restricted Services
- All signals are weak and clustered in the spectrum
  - Allows interoperability
  - But also makes it is relatively easy to jam GNSS and spoof

Time from GNSS:
Intentional and Unintentional Error Sources



Spectra of GNSS's

Primary Commercial Signal



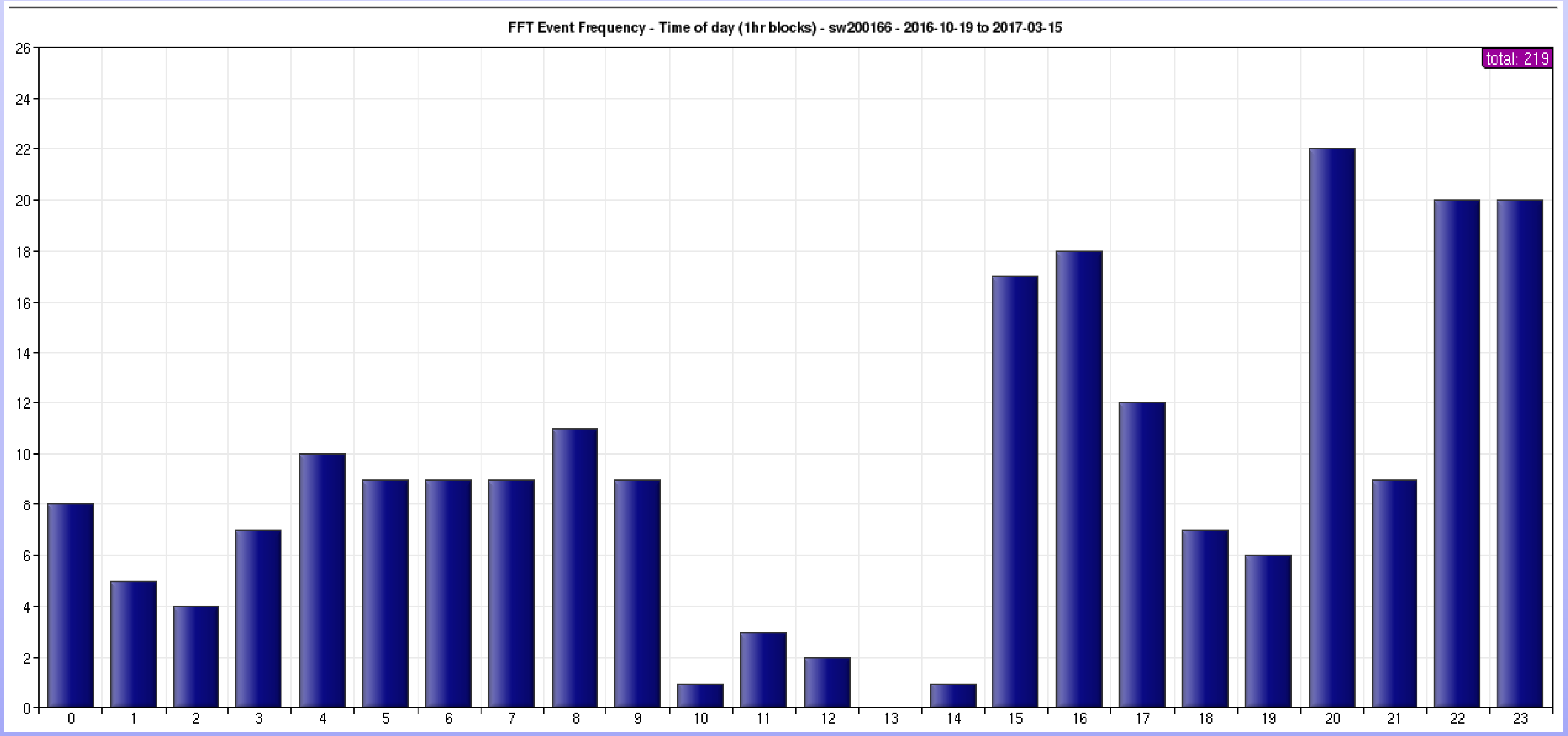
GNSS Vulnerability

- GNSS best feature and worst problem: it is extremely reliable
- Jamming Power Required at GPS Antenna
  - On order of a Picowatt (10^{-12} watt)
- Many Jammer Models Exist
  - Watt to MWatt Output – Worldwide Militaries
  - Lower Power (<100 watts); “Hams” Can Make

•“Personal Privacy”

•Military Jammer

Jamming Events, hour of day since 11/2016



6 PM

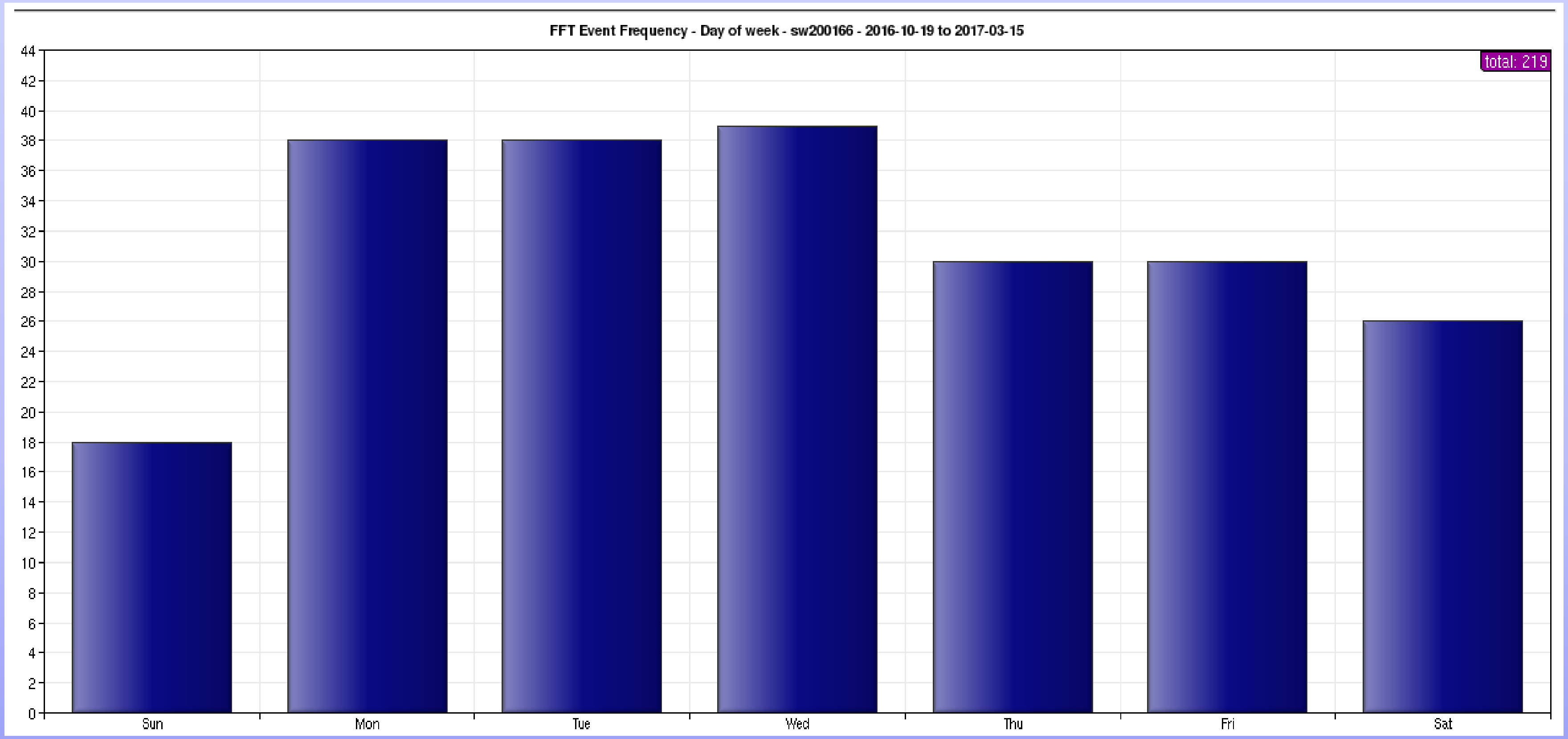
midnight

5 AM

- **Local Time = Pacific**

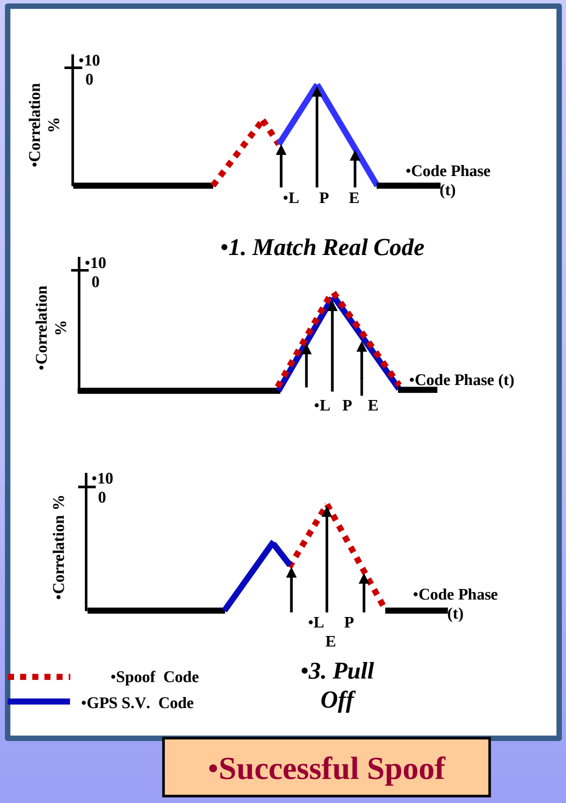
Jamming Detector Courtesy of Prof. Charles Curry BEng, CEng, FIET, Managing Director, Chronos Technology Ltd, UK

Jamming Events, day of week, since 11/2016



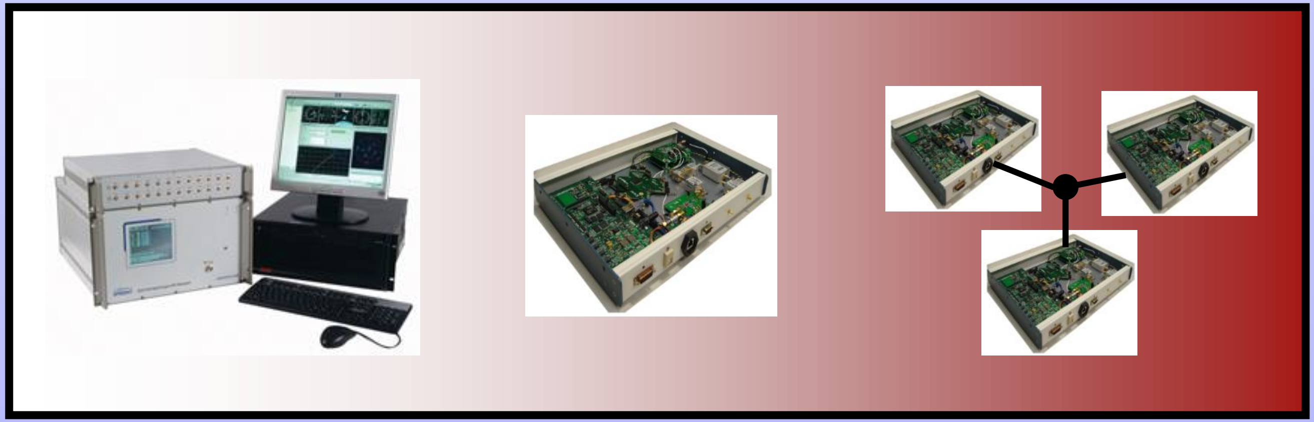
Disruption Mechanisms - Spoofing/Meaconing

- Spoof – Counterfeit GNSS Signal
  - C/A Code Short and Well Known
  - Widely Available Signal Generators
- Meaconing – Delay & Rebroadcast
- Possible Effects
  - Long Range Jamming
  - Injection of Misleading PVT Information
- No "Off-the-Shelf" Mitigation



Civil GPS Spoofing Threat Continuum*

Simplistic *Intermediate* *Sophisticated*



Commercial signal simulator

Portable software radio

Coordinated attack by multiple phase-locked spoofers

•* **Courtesy of Coherent Navigation, Inc**

Spoofing is Now Part of a Game

- In 2017, GPS Spoofing is the real bane of Pokémon GO

- It took us around 90 seconds to setup and successfully start using GPS spoofing on Android:
  - The apps were publicly accessible, hosted on Google Play Store
  - we had almost zero issues with them
  - none of our Android (6) devices were rooted

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Conclusions

- Atomic clocks are accurate and/or stable by design
  - Cs. can be a primary frequency standard
  - Others can be very stable
- Time transfer requires calibration of the delay
  - Two-way cancels the delay if it is symmetric
  - GNSS measures the delay
  - Frequency transfer only requires stable delay
- GNSSs are very accurate both for time and frequency, many signals free for use, and are very reliable
  - Perhaps their greatest advantage and disadvantage!
  - Signals are subject to interference

Thanks for your attention!

Extra slides follow

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Clock Stability

Clock (in)stability is given by:

$$\sigma \approx \frac{\delta f}{f} \propto \frac{1}{Q(S/N)} = \frac{1}{(\bar{\omega}/\Delta\omega)(S/N)}$$

Atomic Line Q **Signal to Noise**

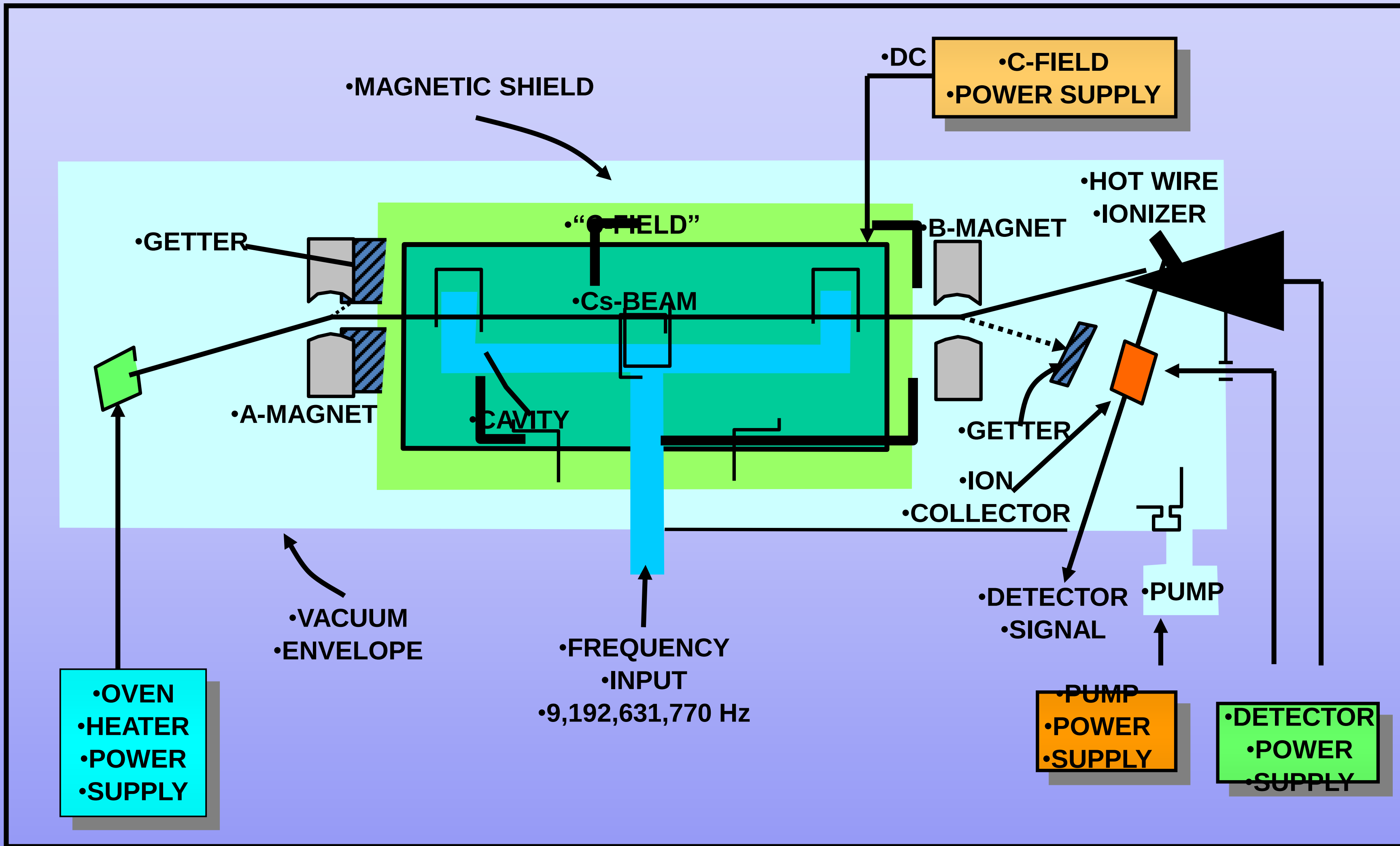
Clock stability can be improved by:

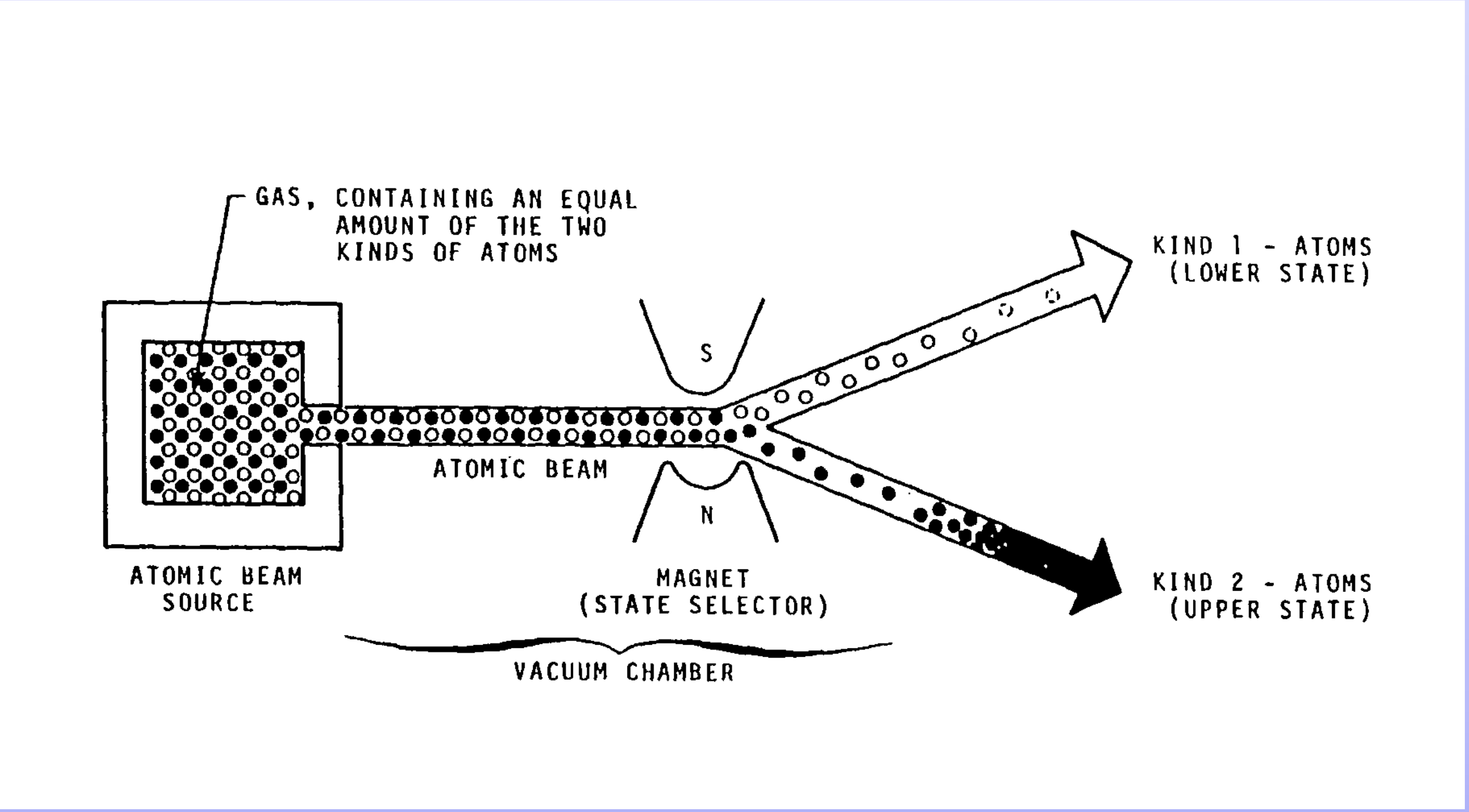
Increase Ramsey (observation) times (decrease $\Delta\omega$=1/T_{Ramsey})

Improve the S/N (more atoms!)

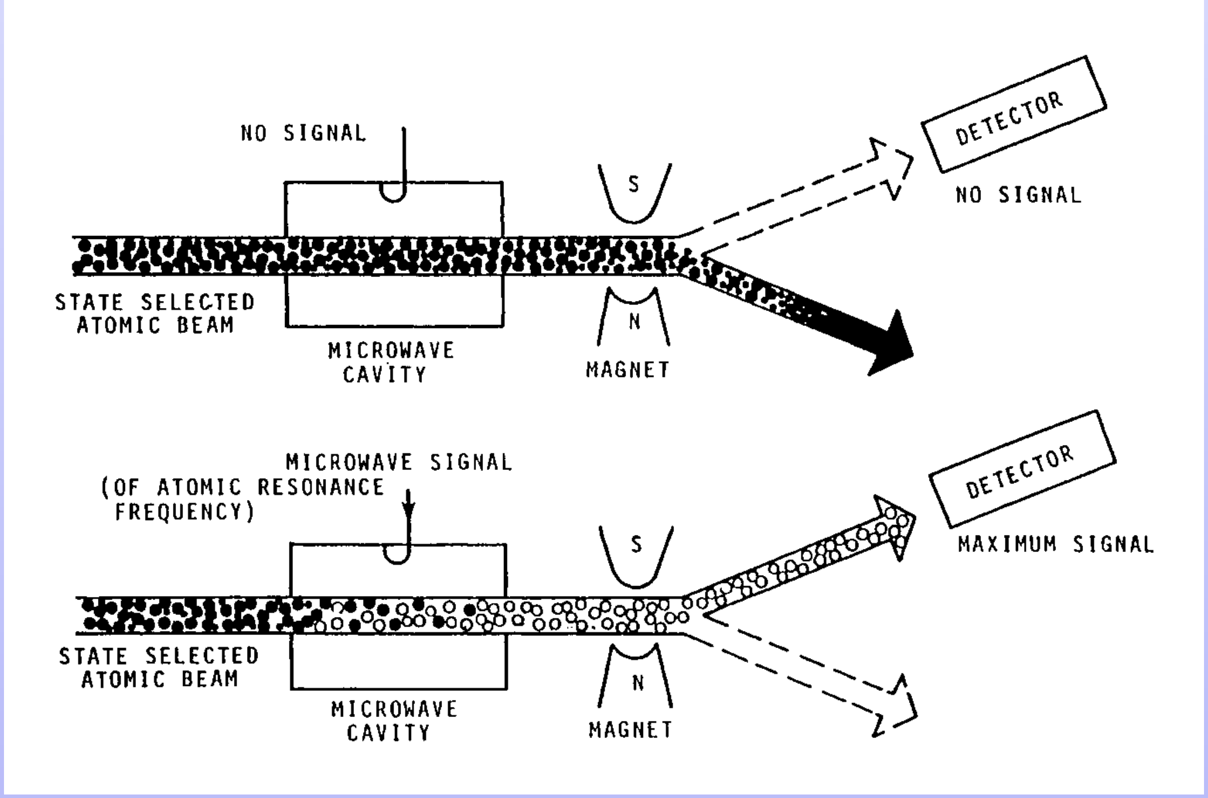
Increase the frequency of the clock transition (optical?)

Cesium Standard





- **Atoms come from an oven in a beam**
-
- **A magnet is used to deflect the atoms in different**
- **hyper-fine states**



- Atoms pass through a Ramsey cavity in a magnetic field to be exposed to microwaves at frequency ν = 9.193 GHz
- A second magnet selects atoms which have made the transition
- The number of detected atoms is used to tune the frequency

Commercial Cesium Standards

•Telecom

•Laboratory/Timekeeping

•Space/GPS

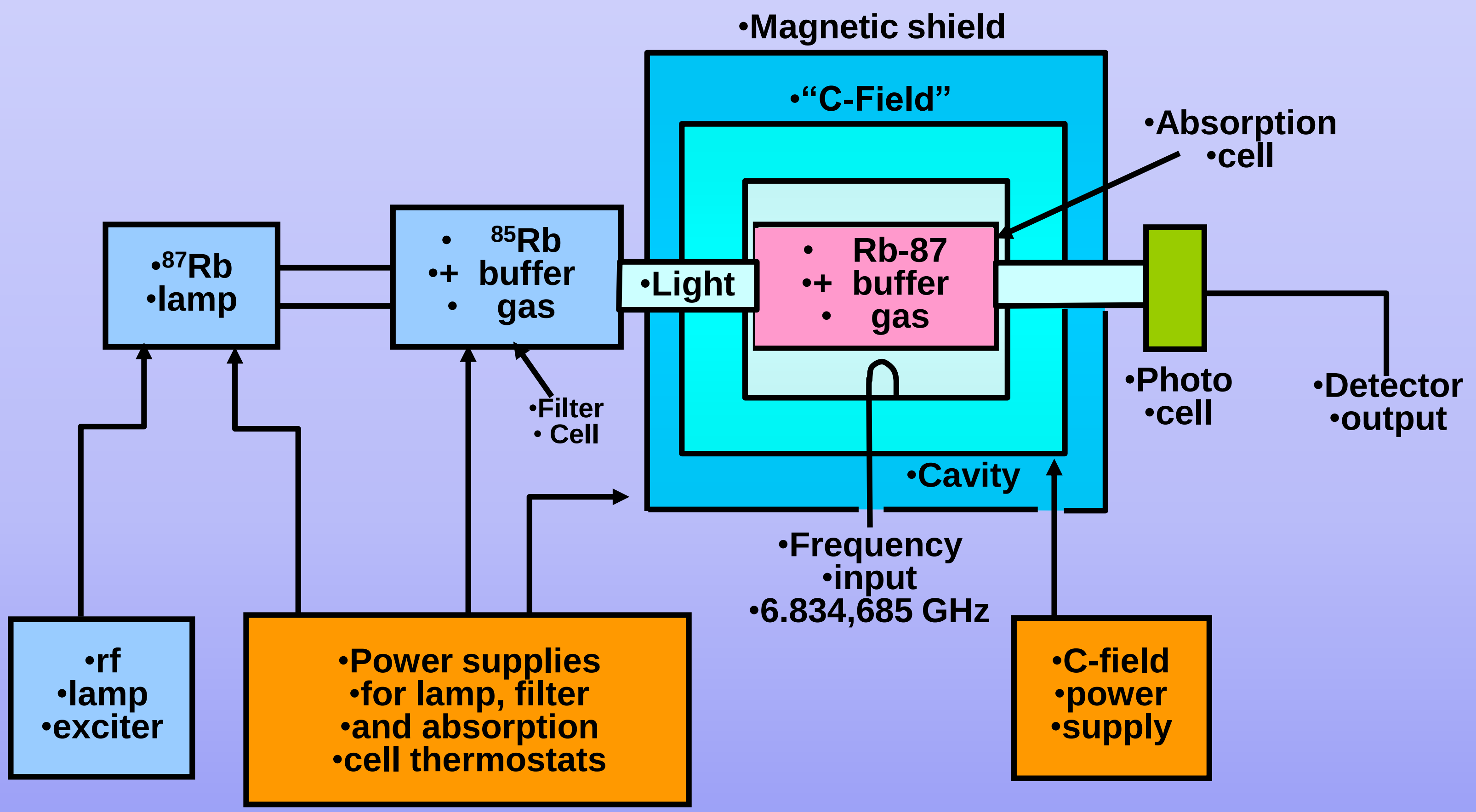
•Courtesy of Robert Lutwak, Symmetricom

Rubidium Standard

- Two major differences from a cesium standard
    1. Cell standard (doesn’t use up rubidium)
    2. Optically pumped (no state selection magnets)

- Used where low cost and small size are important

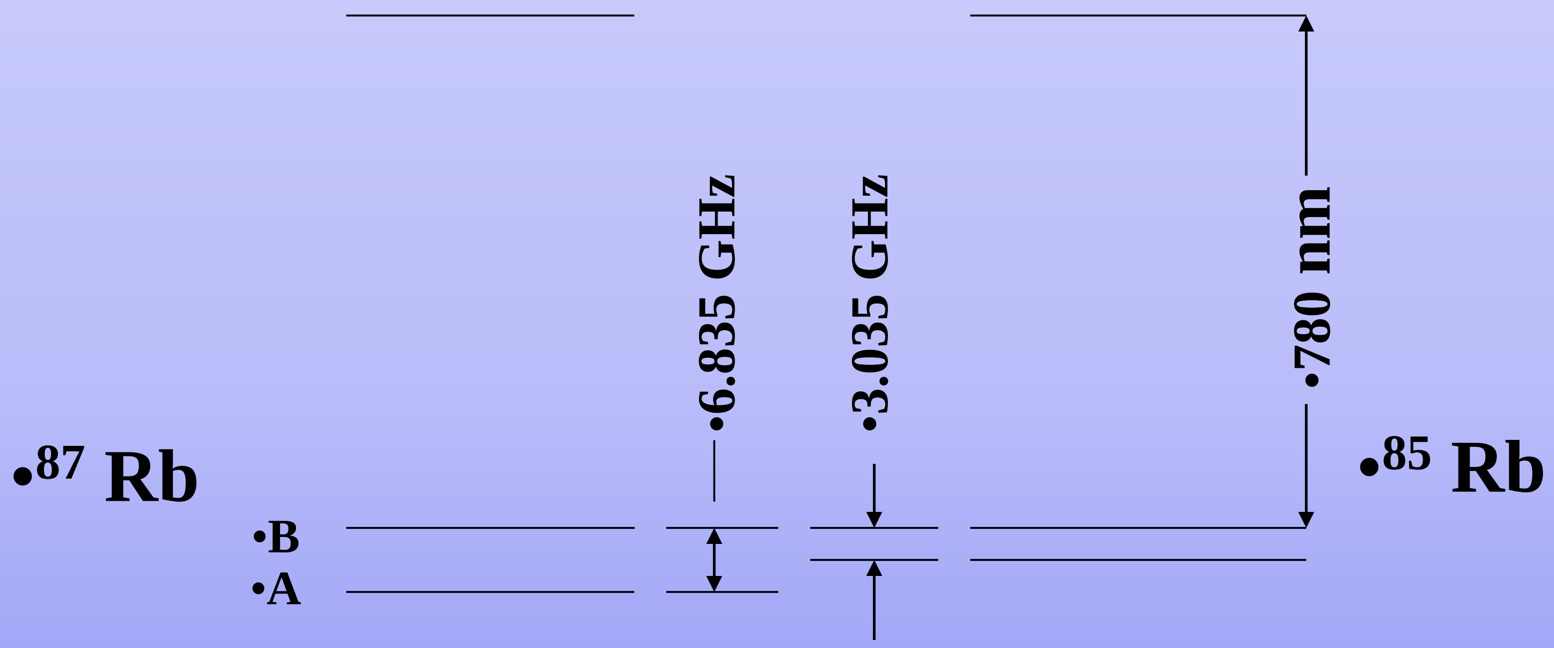
Rubidium Standard

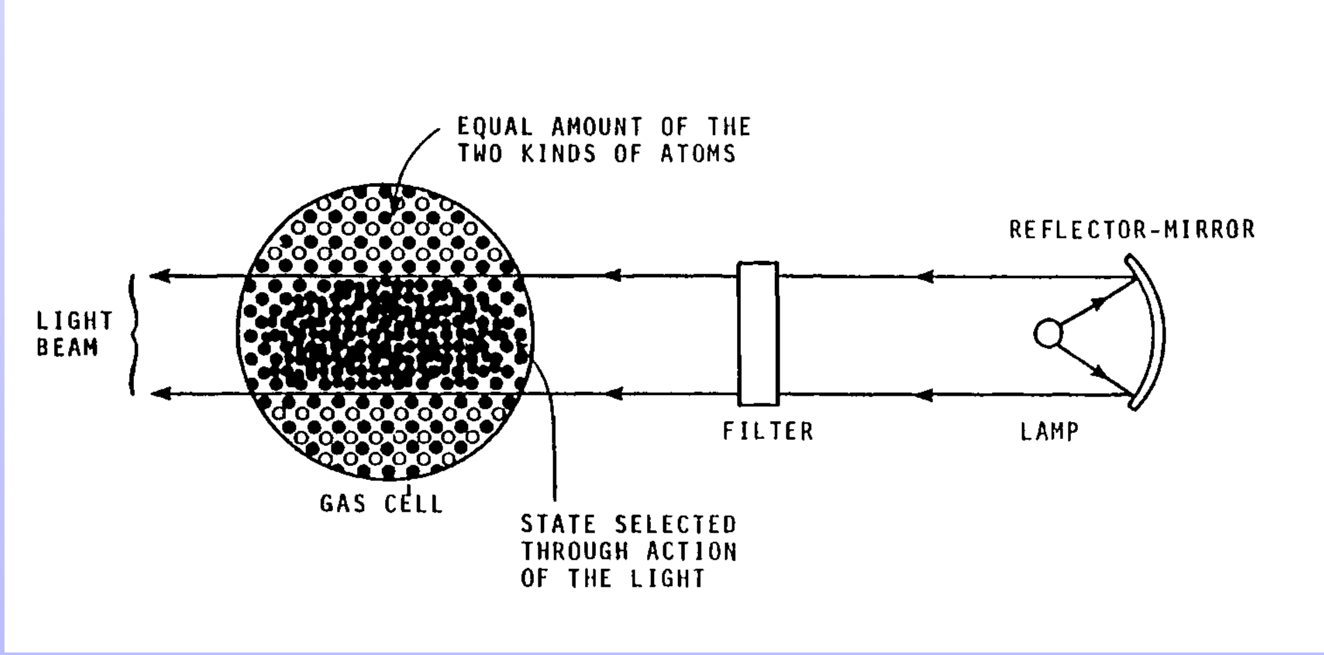


•Adapted from figure by John Vig

Optical Microwave Double Resonance

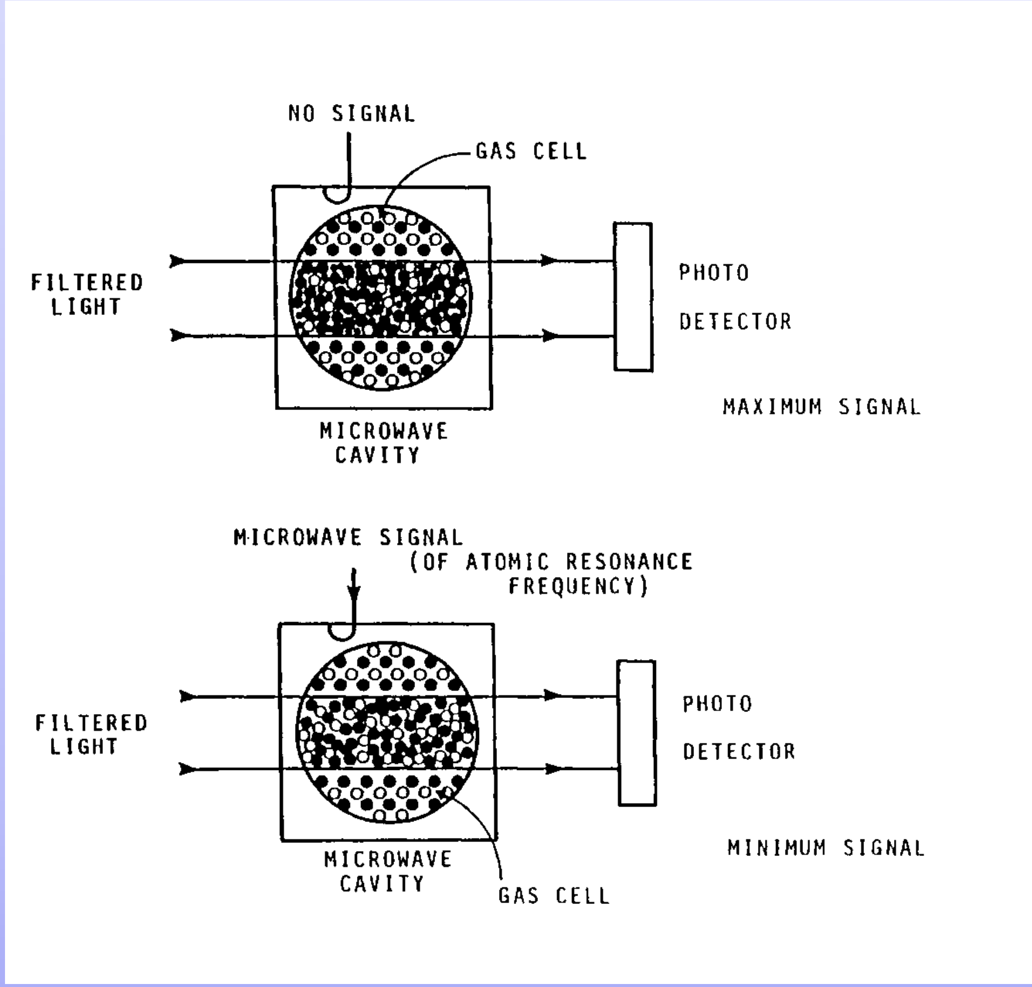
Simplified Rb energy level diagram





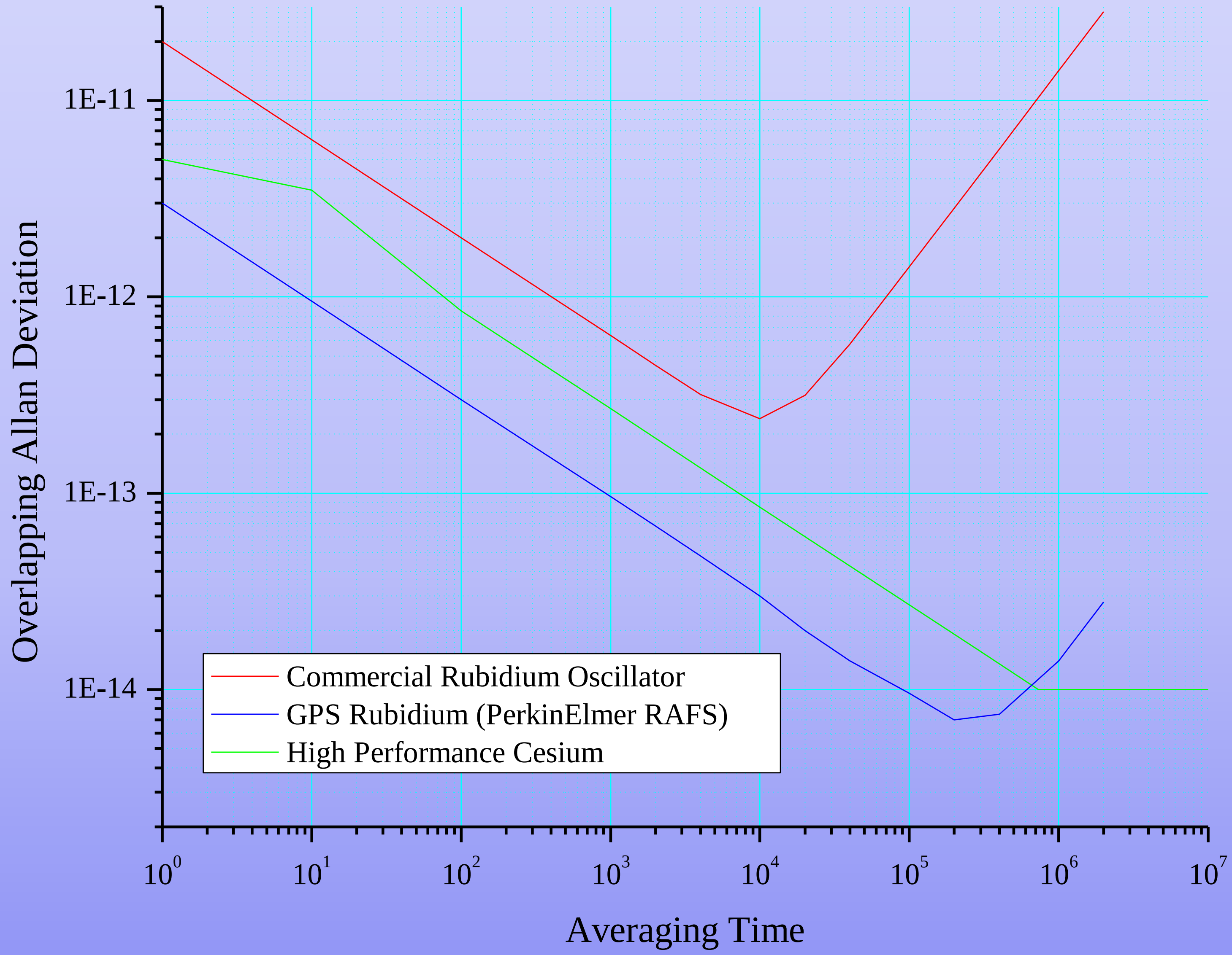
- **Optical pumping is used to deplete one hyper-fine level**

- **Light tuned to the transition frequency from "A" to the**
- **unstable excited state puts all of the atoms in the**
- **hyper-fine state "B"**



- Microwaves at ν = 6.835 GHz stimulate the transition from “B” to “A”
- The absorption of light is measured
- The frequency ν is tuned to minimize the light coming through the ^{87}Rb cell

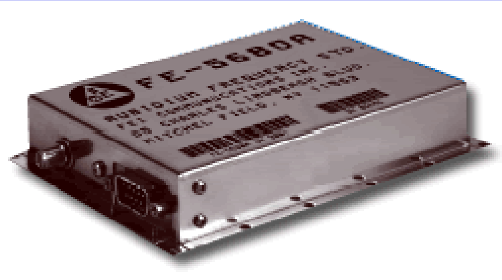
Frequency Stability of a Rubidium Standard



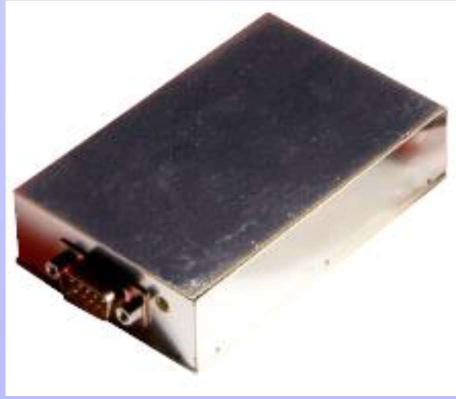
•**Courtesy of Robert Lutwak, Symmetricom**

Commercial Rubidium Standards

•Stanford Research PRS10



•Frequency Electronics
• FE-5680A



•Quartzlock E10

•Temex SR100

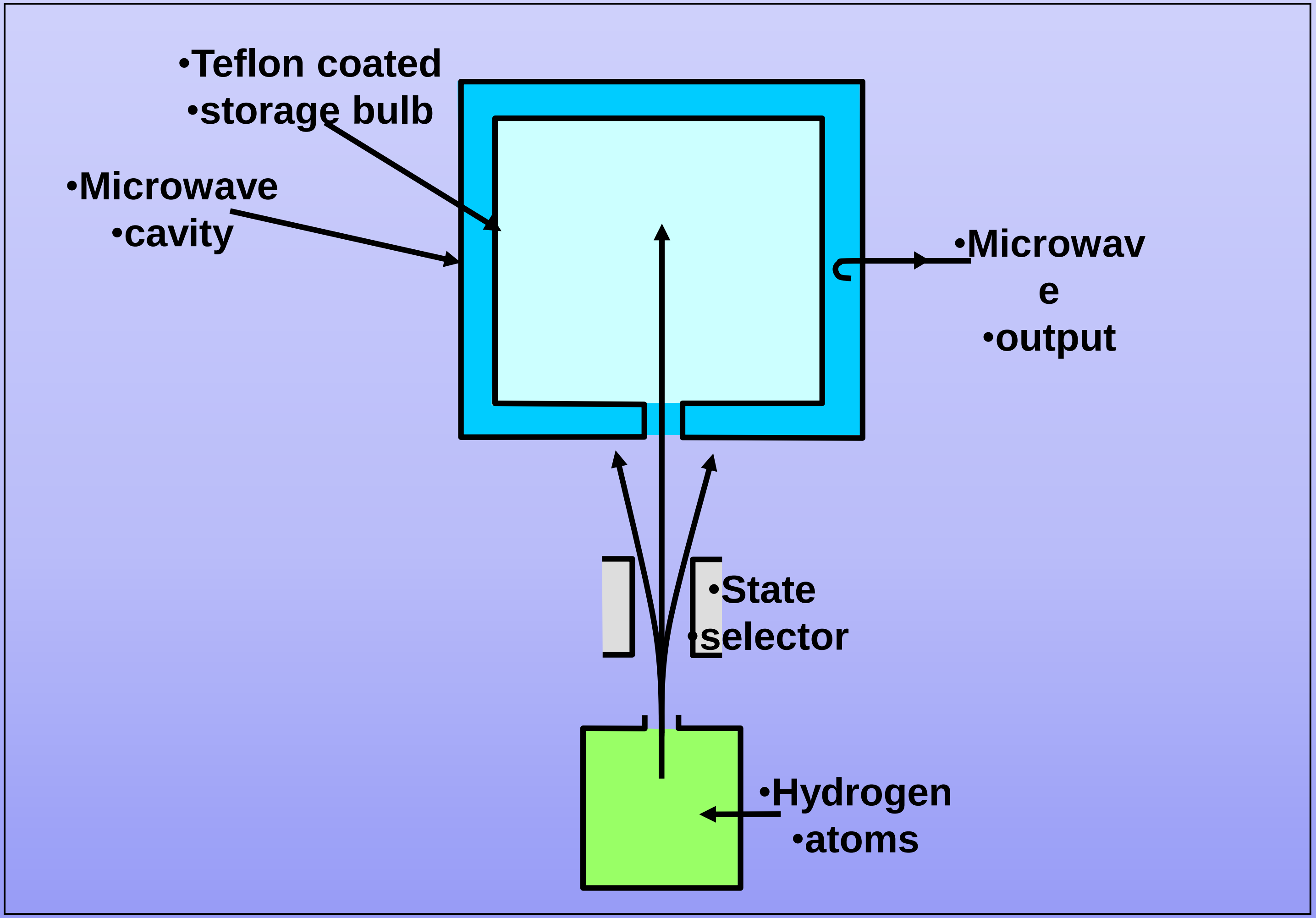
•PerkinElmer GPS RAFS

•Symmetricom X72

•Accubeat AR-70A

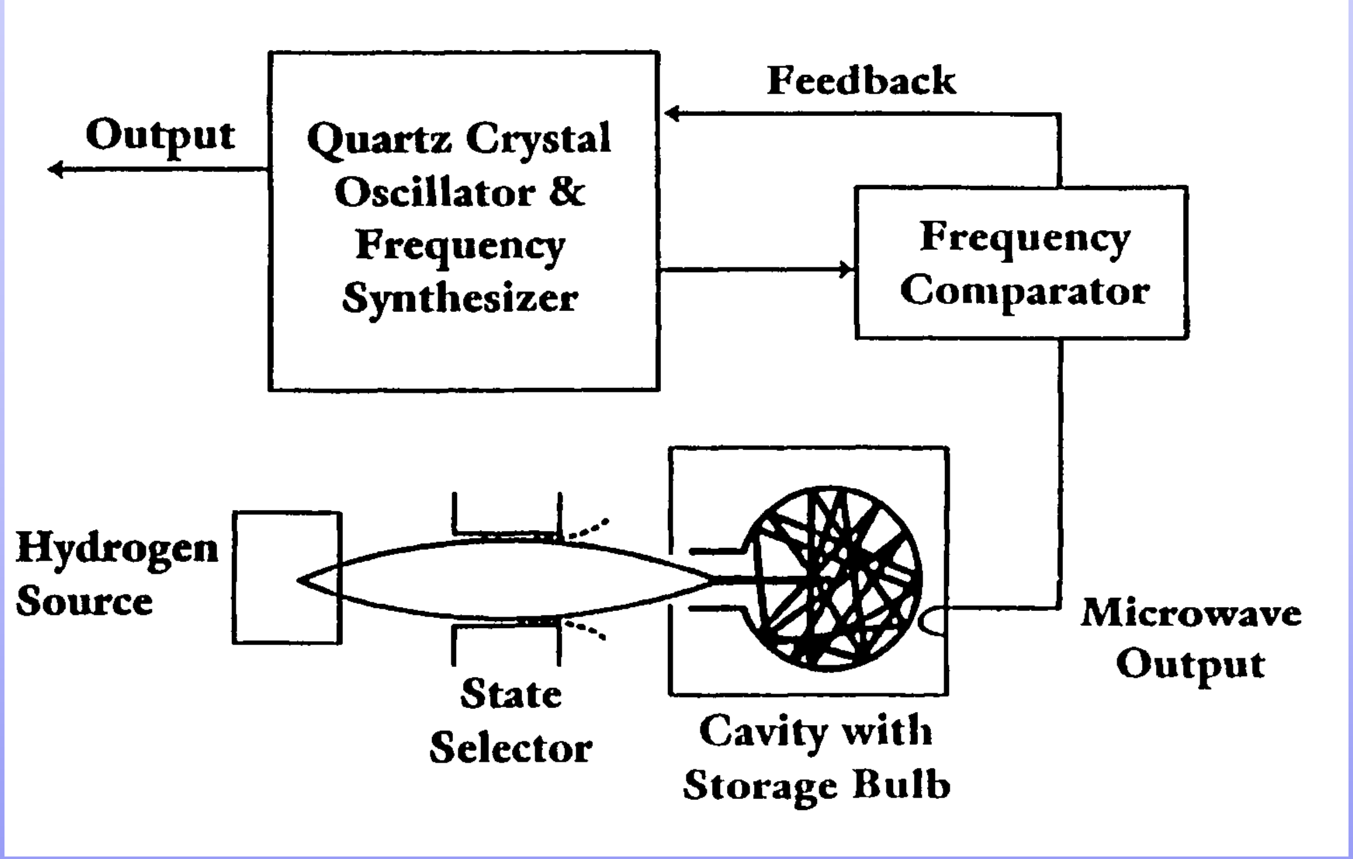
•Courtesy of Robert Lutwak, Symmetricom

Hydrogen Maser
(Active Standard)

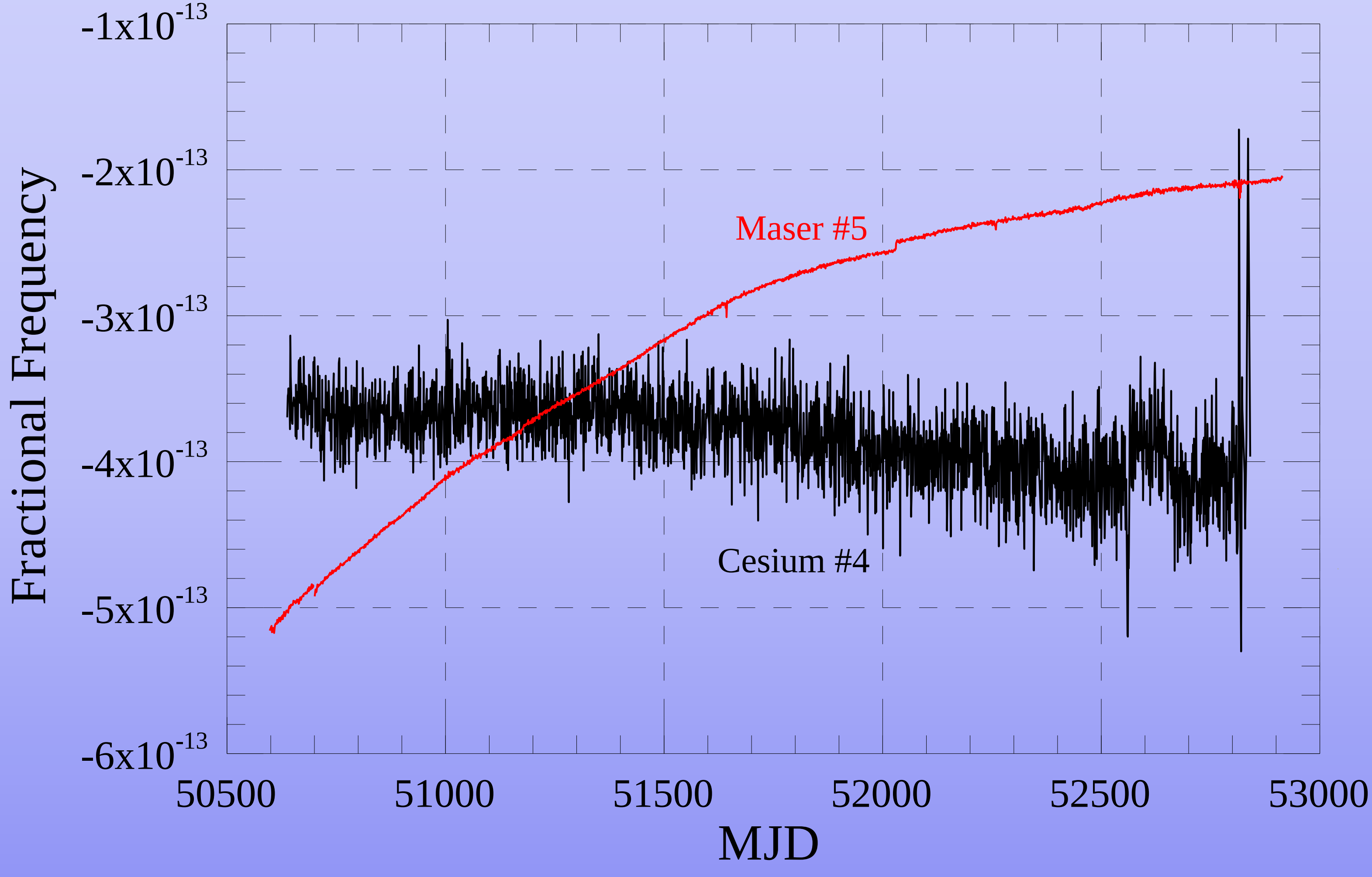


•Adapted from a figure by John Vig

Hydrogen Maser
(Active Standard)

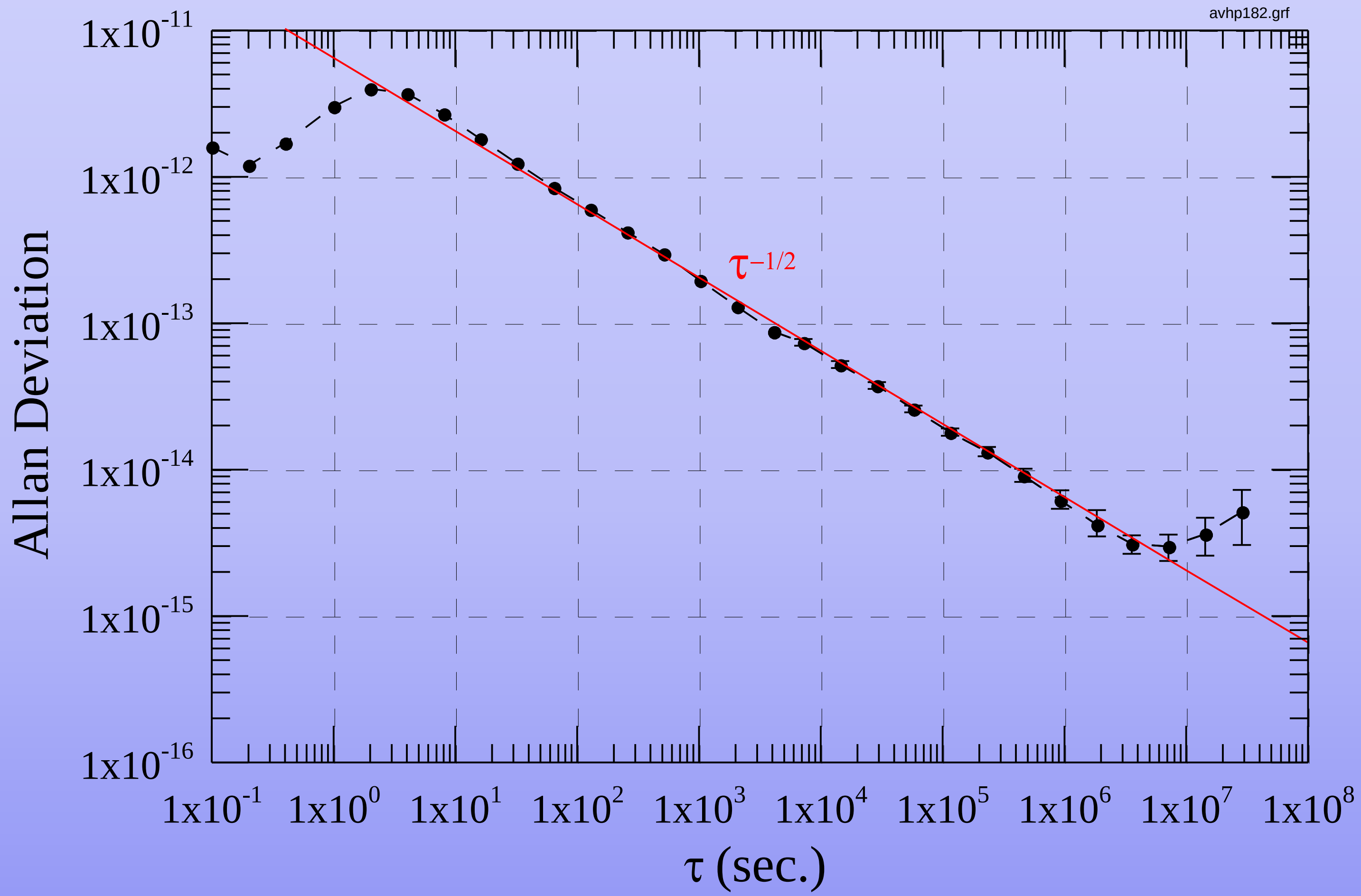


Frequency Drift of a Commercial Cesium Standard and a Hydrogen Maser



Frequency Stability of a Cesium Standard

(No frequency drift removed)

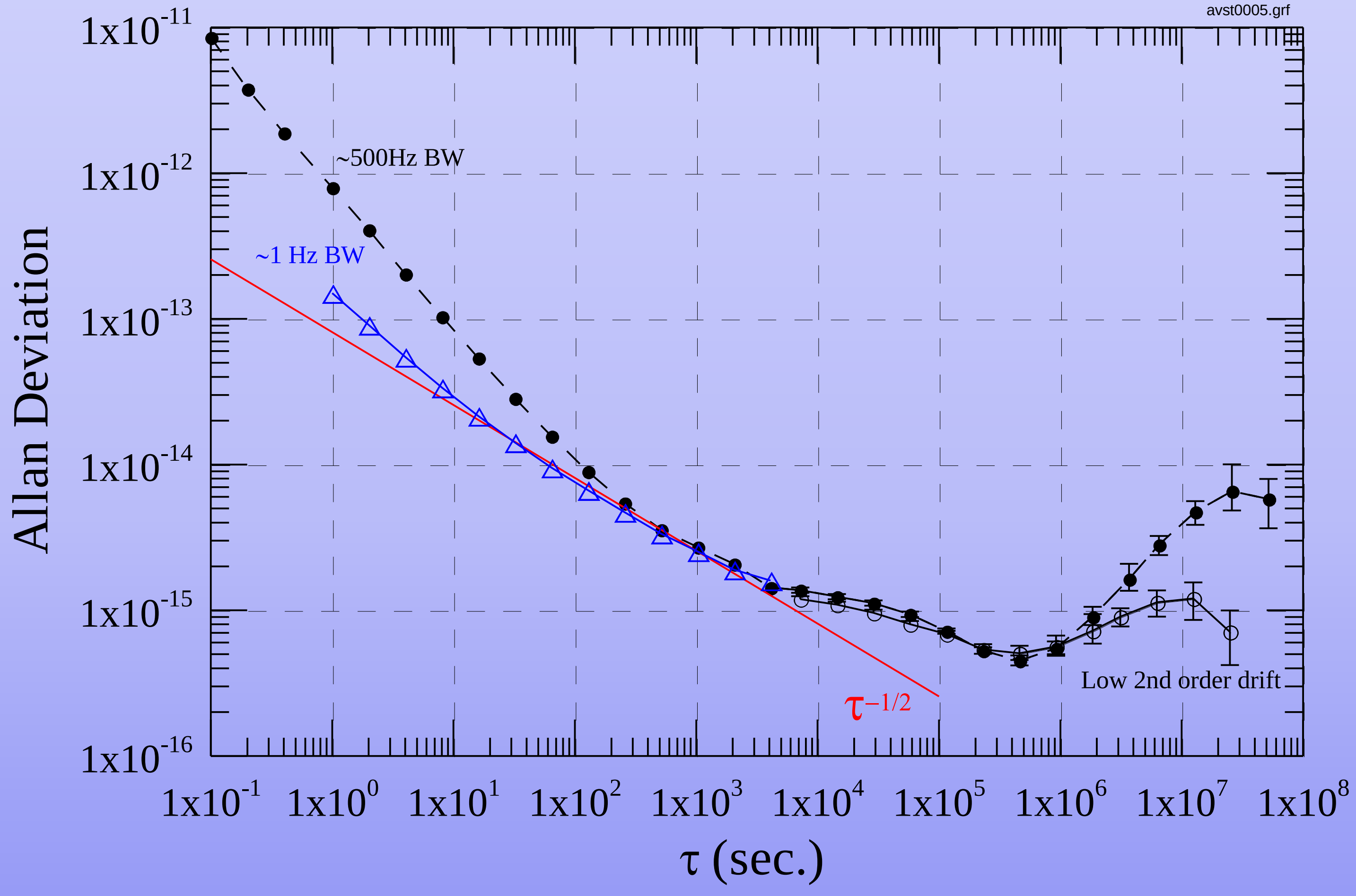


Commercial Active Hydrogen Maser

•**Courtesy of Robert Lutwak, Symmetricom**

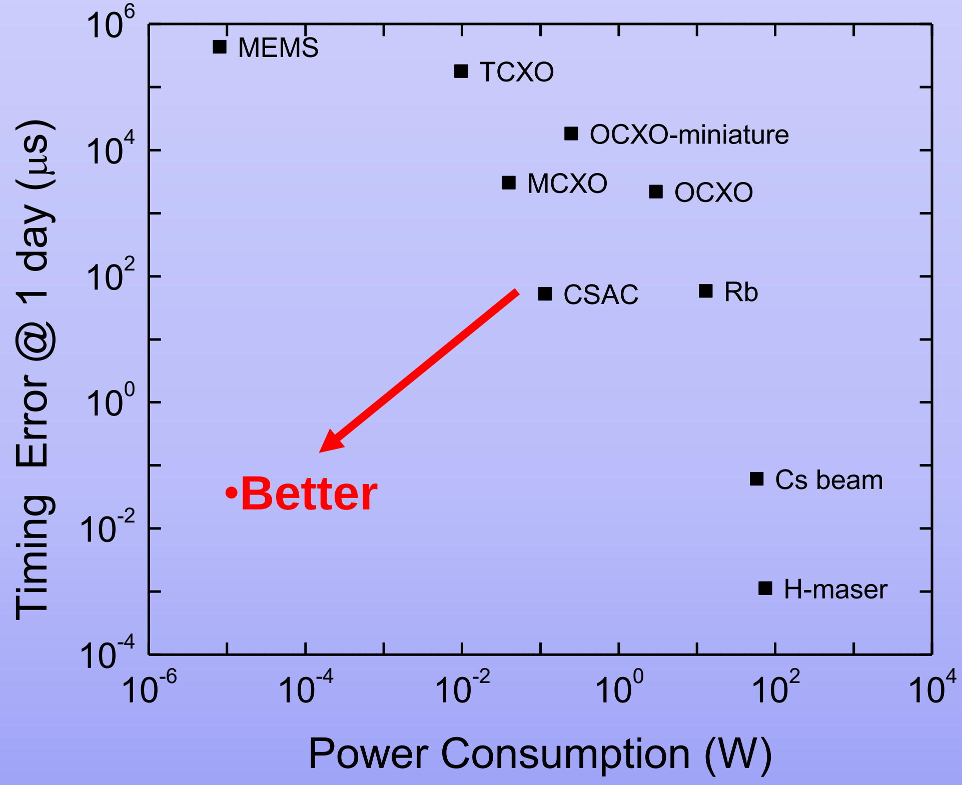
Frequency Stability of a Hydrogen Maser

(Frequency drift removed – $1x10^{-16}$/day typical)



Something New!

- Chip Scale Atomic Clock (CSAC)
    1. Cesium cell standard
    2. Coherent Population Trapping (CPT)
- Very small size and low power consumption, but better performance than a quartz oscillator



MEMS
TCXO
OCXO-miniature
MCXO
OCXO
CSAC
Rb
Cs beam
H-maser
•Better
Timing Error @ 1 day (μs)
Power Consumption (W)

Oscillator Comparison

Technology	Intrinsic Accuracy	Stability (1s)	Stability (floor)	Aging (/day) initial to ultimate	Applications
Cheap Quartz, TCXO	10^{-6}	$\sim 10^{-11}$	$\sim 10^{-11}$	10^{-7} to 10^{-8}	Wristwatch, computer, cell phone, household clock/appliance,…
Hi-quality Quartz, OCXO	10^{-8}	$\sim 10^{-12}$	$\sim 10^{-12}$	10^{-9} to 10^{-11}	Network sync, test equipment, radar, comms, nav,…
Rb Oscillator	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	Wireless comms infrastructure, lab equipment, GPS, …
Cesium Beam	$\sim 10^{-13}$	$\sim 10^{-11}$	$\sim 10^{-14}$	nil	Timekeeping, Navigation, GPS, Science, Wireline comms infrastructure,…
Hydrogen Maser	$\sim 10^{-11}$	$\sim 10^{-13}$	$\sim 10^{-15}$	10^{-15} to 10^{-16}	Timekeeping, Radio astronomy, Science,…

•**Courtesy of Robert Lutwak, Symmetricom**

Oscillator Comparison (continued)

Technology	Size	Weight	Power	World Market	Cost
Cheap Quartz, TCXO	≈ 1 cm^3	≈ 10 g	≈ 10 mW	≈ 10^9s/year	≈ $1s
Hi-quality Quartz, OCXO	≈ 50 cm^3	≈ 500 g	≈ 10 W	≈ 10Ks/year	≈ $100s
Rb Oscillator	≈ 200 cm^3	≈ 500 g	≈ 10 W	≈ 10Ks/year	≈ $1000s
Cesium Beam	≈ 30,000 cm^3	≈ 20 kg	≈ 50 W	≈ 100s/year	≈ $10Ks
Hydrogen Maser	≈ 1 m^3	≈ 200 kg	≈ 100 W	≈ 10s/year	≈ $100Ks

•**Courtesy of Robert Lutwak, Symmetricom**

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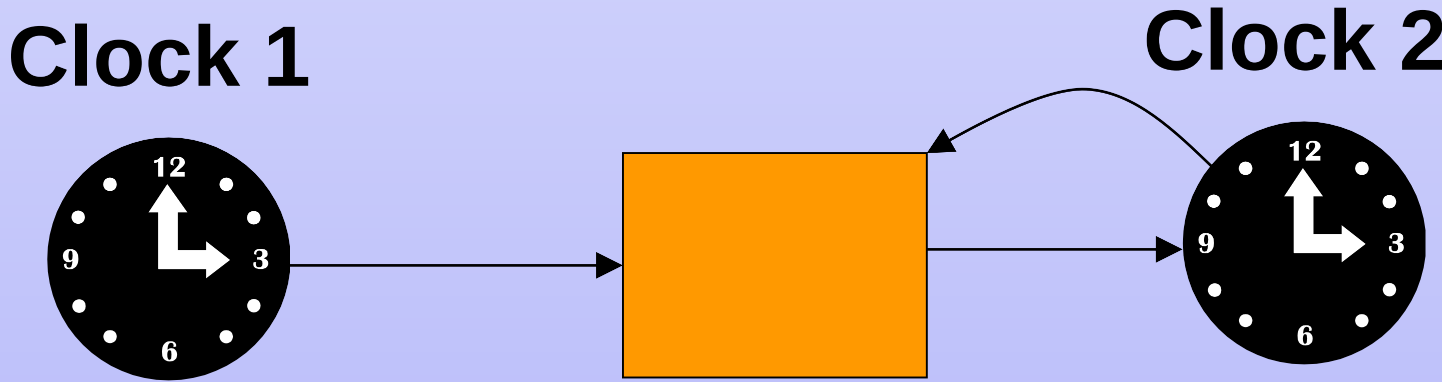
Time and Frequency Transfer

- Accuracy and Stability are the Concerns
  - Time Transfer Accuracy Requires Calibrating Delays
  - Time Stability = Frequency Accuracy

- Continuous vs Intermittent Measurements

Clock Hierarchies

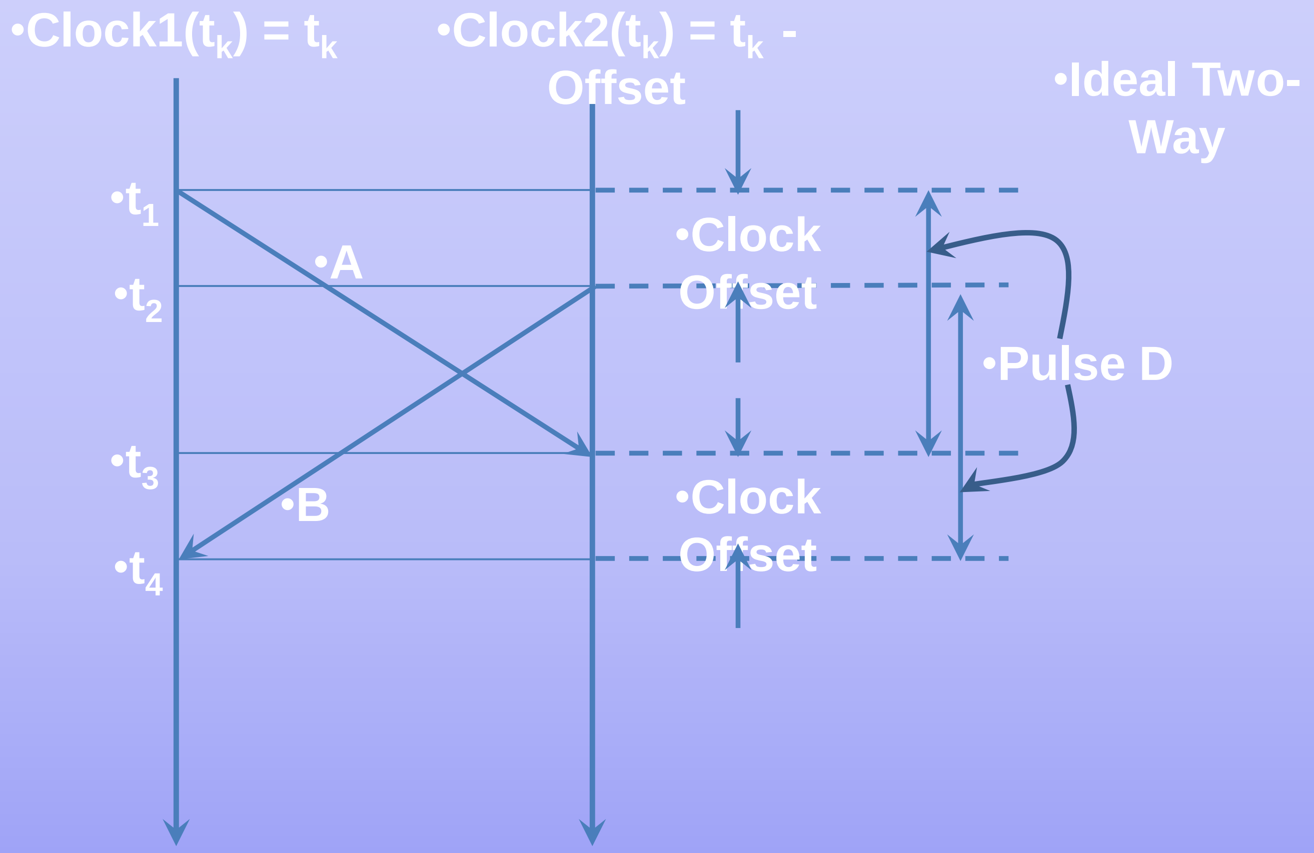


Clock 1 Systematics and Noise

Lock Loop Systematics and Noise: Contributions from Delay, Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Two-Way has Four Time Stamps



Ideal Two-Way Computation

- Signal A: t_{31}= Clock2(t_3) - Clock1(t_1)
- Signal B: t_{42}= Clock1(t_4) – Clock2(t_2)
- Assume Clock1 is correct, Clock2 has an offset or error *E*, and Delays, *D*, are reciprocal
  - Clock1(t_j) = t_j, Clock2(t_j) = $t_j - E$
  - Transmission times on local clocks: Clock2(t_2)= Clock1(t_1), i.e. $t_2 = t_1 + E$
  - Reciprocal Delays: $d_{12} = d_{21} = D$
- Then $t_2 = t_1 + E$, $t_3 = t_1 + D$, $t_4 = t_2 + D$
- Then t_{31} = Clock2(t_3) - Clock1(t_1) = $t_3 - E - t_1 = t_1 + D - E - t_1 = D - E$
- And t_{42}= Clock1(t_4) – Clock2(t_2) = $t_4 - (t_2 - E) = t_2 + D - (t_2 - E) = D + E$
- Therefore
  - $D = ½ (t_{42} + t_{31})$
  - $E = ½ (t_{42} - t_{31})$

Synchronization vs Syntonization

Two Separate Concepts
Both called “Synchronization” in Telecom

Synchronization

- Same Time
- Same Phase
- Phase Lock

Syntonization

- Same Frequency
- Frequency Lock $\Rightarrow$ Phase Offset Unbounded

How to Characterize Attributes of Time and Frequency Transfer Systems

1. Time Transfer Accuracy
    1. Agreement with the "true" clock difference
    2. Evaluate with a more accurate transfer system
    3. Never better than stability
2. Time Transfer Stability -- Plot x(t)
    1. TDEV, $\sigma_x(\tau)$
    2. Spectrum, $S_x(f)$
3. Frequency Transfer Accuracy
    1. Directly related to time transfer stability
    2. A function of averaging time, τ, and processing
4. Frequency Transfer Stability-- Plot y(t)
    1. ADEV, $\sigma_y(\tau)$
    2. Spectrum, $S_y(f)$
    3. Estimate Drift

Summary:
Time and Frequency Transfer Systems

- Time: Calibrate the Delay
- Stability: Keep the delay constant
- Issues
  - Accuracy
  - Stability
  - Uncertainty
  - Systematic vs Random Deviations
- Syntonization vs Synchronization

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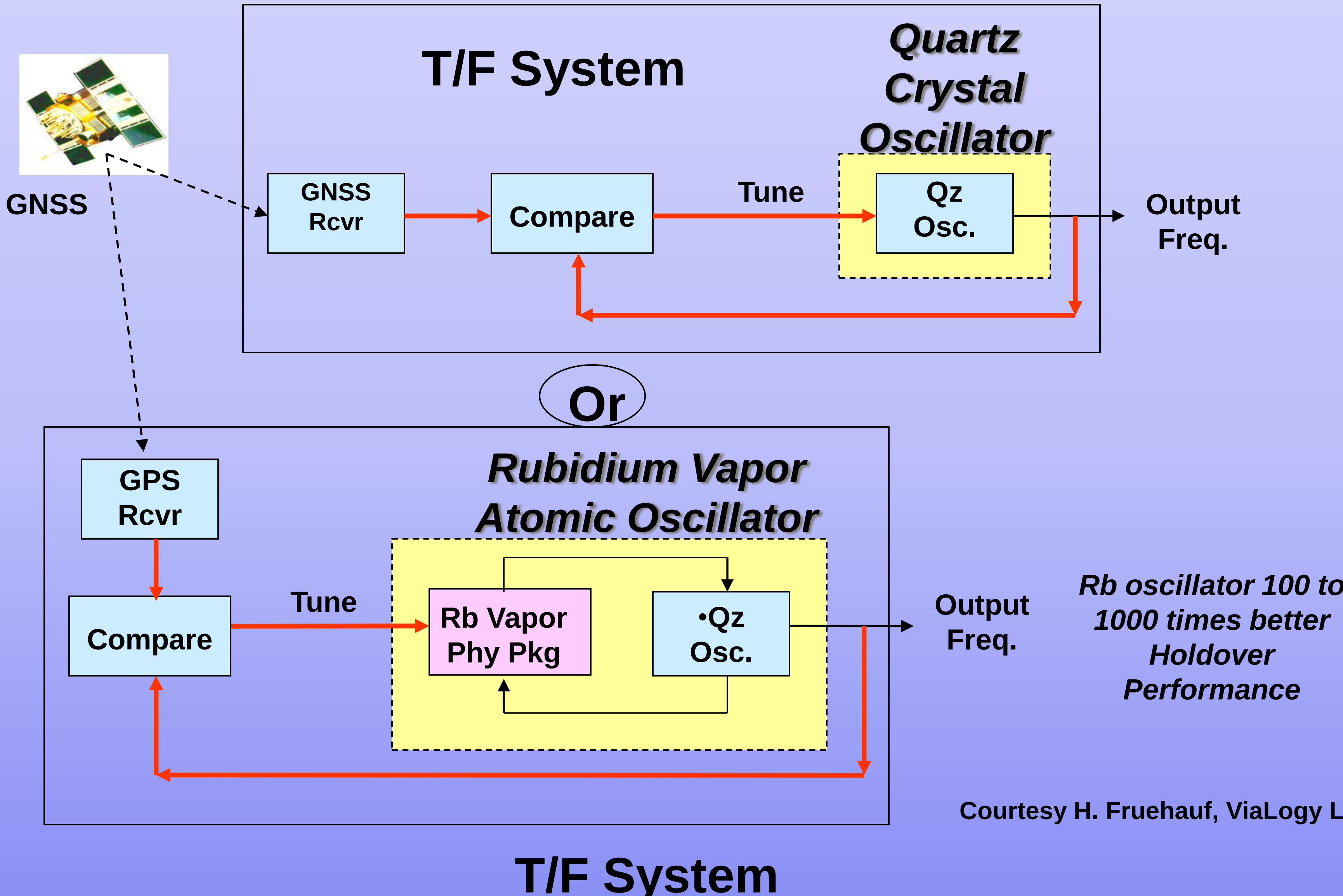
Time From GNSS

- Clocks on Satellite Vehicles (SVs) are free-running
  - Data provides the offset in Time and Frequency
  - System time is offset from UTC
- The positions of the satellite and receiver are needed for the delay
- SV Clocks and positions are ***predicted*** and uploaded, for GPS about once per day

GNSS-aided Time and Frequency Systems



Courtesy H. Fruehauf, ViaLogy LLC

Jamming Detector, Qulsar, San Jose

- Jamming Detector Courtesy of Prof. Charles Curry BEng, CEng, FIET, Managing Director, Chronos Technology Ltd, UK

GNSS References

- GPS
  - CGSIC 2013 http://www.gps.gov/cgsic/meetings/2013/
  - Coast Guard Nav Center http://www.navcen.uscg.gov/
- Galileo http://www.gsc-europa.eu/system-status/Constellation-Information
- Glonass http://www.sdcm.ru/smglo/grupglo?version=eng&site=extern
- Beidou:
  - IGS page http://igs.org/mgex/Status_BDS.htm
- General
  - GPS World http://gpsworld.com/
  - Inside GNSS http://www.insidegnss.com/